LA-UR-17-25076

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Title: Walking the road from impacts to seismic sources.

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Intended for: Report

Issued: 2017-06-23

Walking the Road from Impacts to Seismic Sources

LDRD-ER Proposal

09 May 2017

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EES-17

Background & Motivation

NASA needs a proven source model to exploit impact analysis for future seismic missions!

Seismic exploration can become a game changer. However, the program lacks reliable seismic source impact models.

Table 1: Estimates of the Impact Seismic Efficiency factor, η, span several orders of magnitude		
Author	Source	η
Gault and Heitowit (1963)	Laboratory impact experiments	10^{-2}
Titley (1966)	Nuclear and other large explosion sources	3×10^{-1} - 3×10^{-3}
McGarr et al. (1969)	Laboratory impact experiments	10^{-4} - 10^{-6}
Latham, McDonald and Moore (1970)	White Sands missile range impacts on Earth	10^{-5} - 5×10^{-5}
Latham, McDonald and Moore (1970)	Low angle spacecraft impacts on the Moon	10^{-5} - 10^{-6}
Schultz and Gault (1975	Various sources	10^{-3} - 10^{-5}

Seismic efficiency **is a first-order parameter of the seismic source whose estimation varies from 10^{-5} to 10^{-2}.**

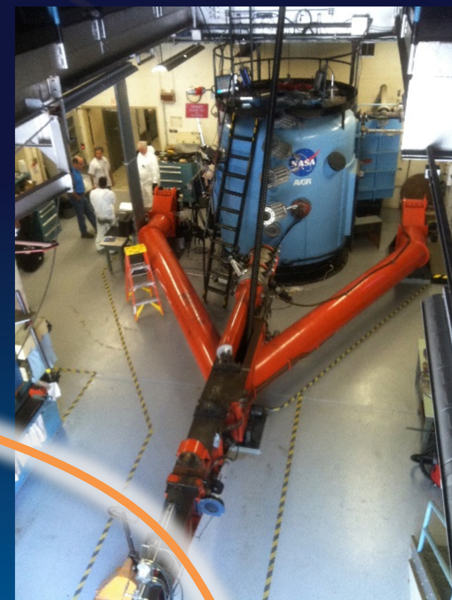
Such uncertainty translates into mission risk and mission complexity.

Collaboration and programmatic landscape

Data analysis of Insight is an international effort of top institutions: NASA, JPL, IPGP, ETH, MPS, CNES, Imperial College of London, University of Oxford, Supaero, CNRS, Max-Planck university.

- Dr. P. Lognonné, the PI of SEIS, the seismometer to be sent in Insight, identified the LANL team as having modeling capabilities lacking in the science team involved in Insight.
- Dr. S. Kedar, JPL, was contacted and confirmed the need for advanced modeling.

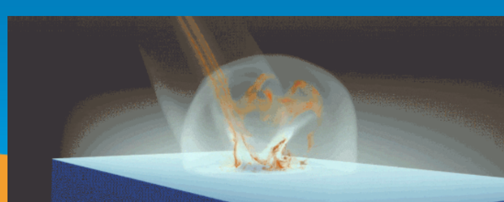
- Dr. Cathy Plesko (LANL) is now collaborating with us for validation effort and her modeling of kinematic impactor.

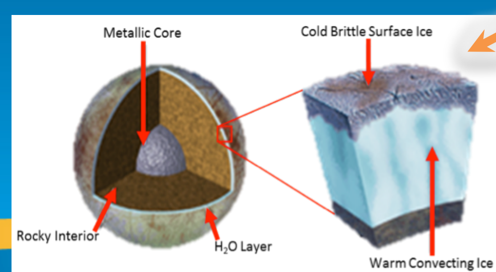


AVGR facility

Mars (2018)

Moon





Europe

Innovation

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- Challenge: The most direct way to estimate the detectability of impact sources requires obtaining an accurate ***source-time-function***, i.e., the time history of force transfer into the elastic medium that results from the highly complex and non-linear impact process. To date, this has not been achieved due to the limitations of state-of-the-art impact models.

Our research plan is to develop new impact models based on high-fidelity simulations and observations.

- *Partnership between LANL, IPGP, and JPL represents a unique scientific opportunity to develop new impact models.*
- *LANL brings in HPC resources and leadership into the simulation of extreme events, such as seismic sources, as demonstrated by the success of our team in modeling underground nuclear explosions.*
- *IPGP and JPL bring in unique datasets of remarkable quality: (1) high speed impact data from experiments conducted at the NASA AVGR; (2) seismic recordings of impacts on the Moon (Lunar Excursion Module and Saturn rocket's S-IVB stage).*

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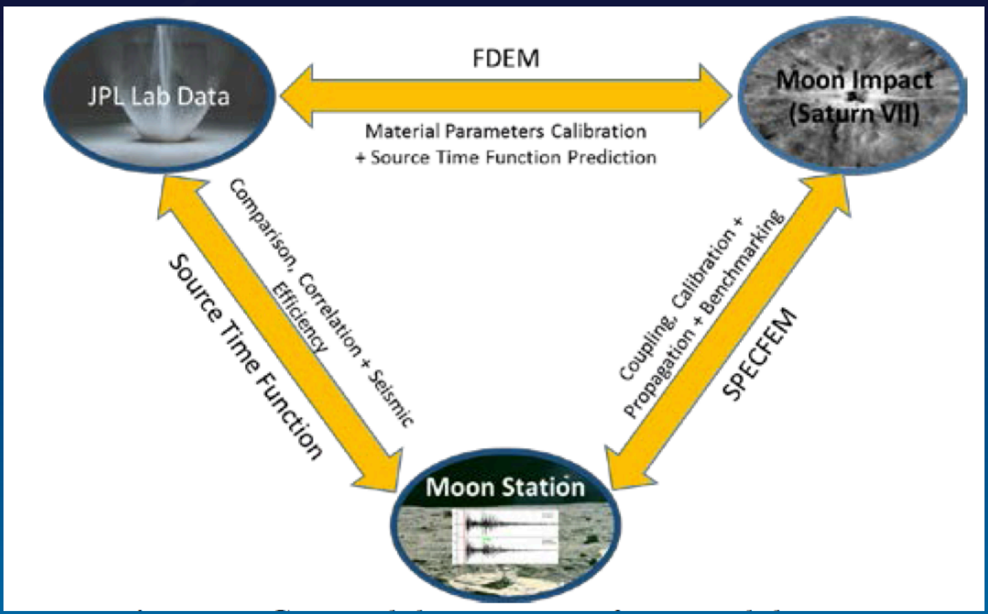
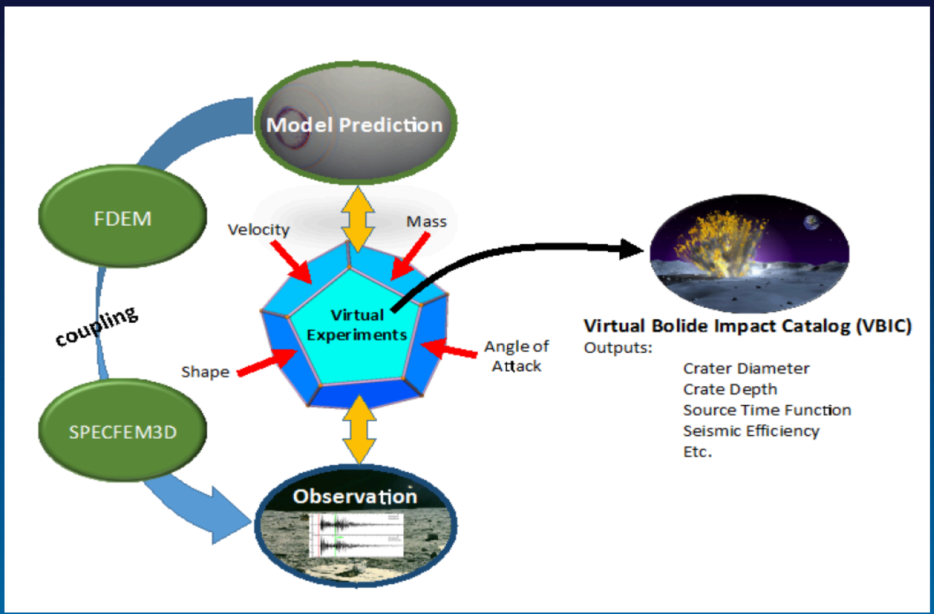
Description

Our approach is to extend our proven modeling capabilities to unconsolidated soils and high-velocity impacts.



Using three different data scales to refine models.



integration of data and simulation results into the Virtual Bolide Impact Catalog (VBIC).

Innovation comes from modeling expertise at LANL and the use of dataset of different scales and qualities..
We envision that the created VBIC to be broadly used for validation and calibration in multiple applications.

Effective bolide impact analysis requires high-fidelity modeling: two codes for one mission

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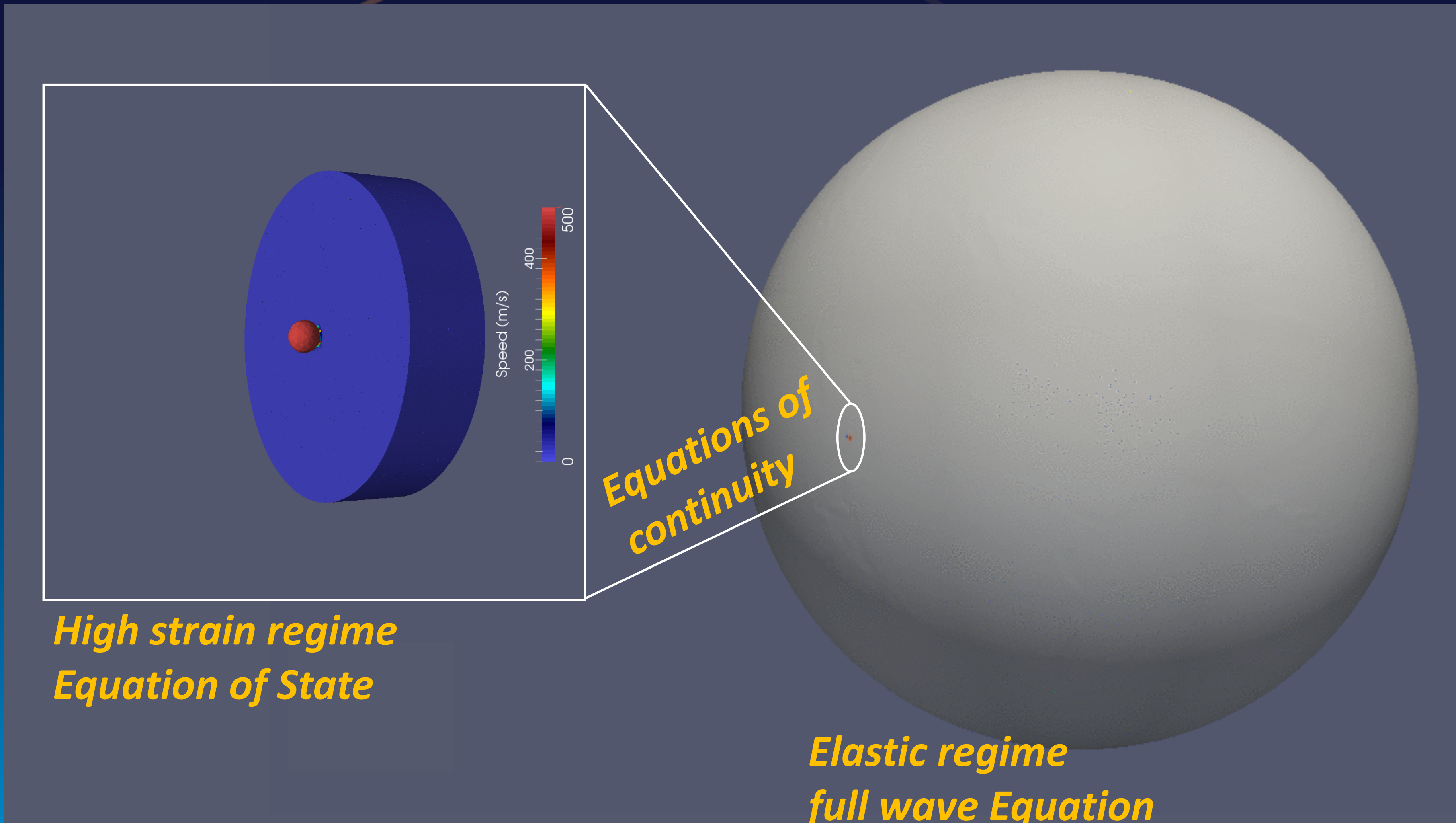

Two codes coupled using continuity equations.

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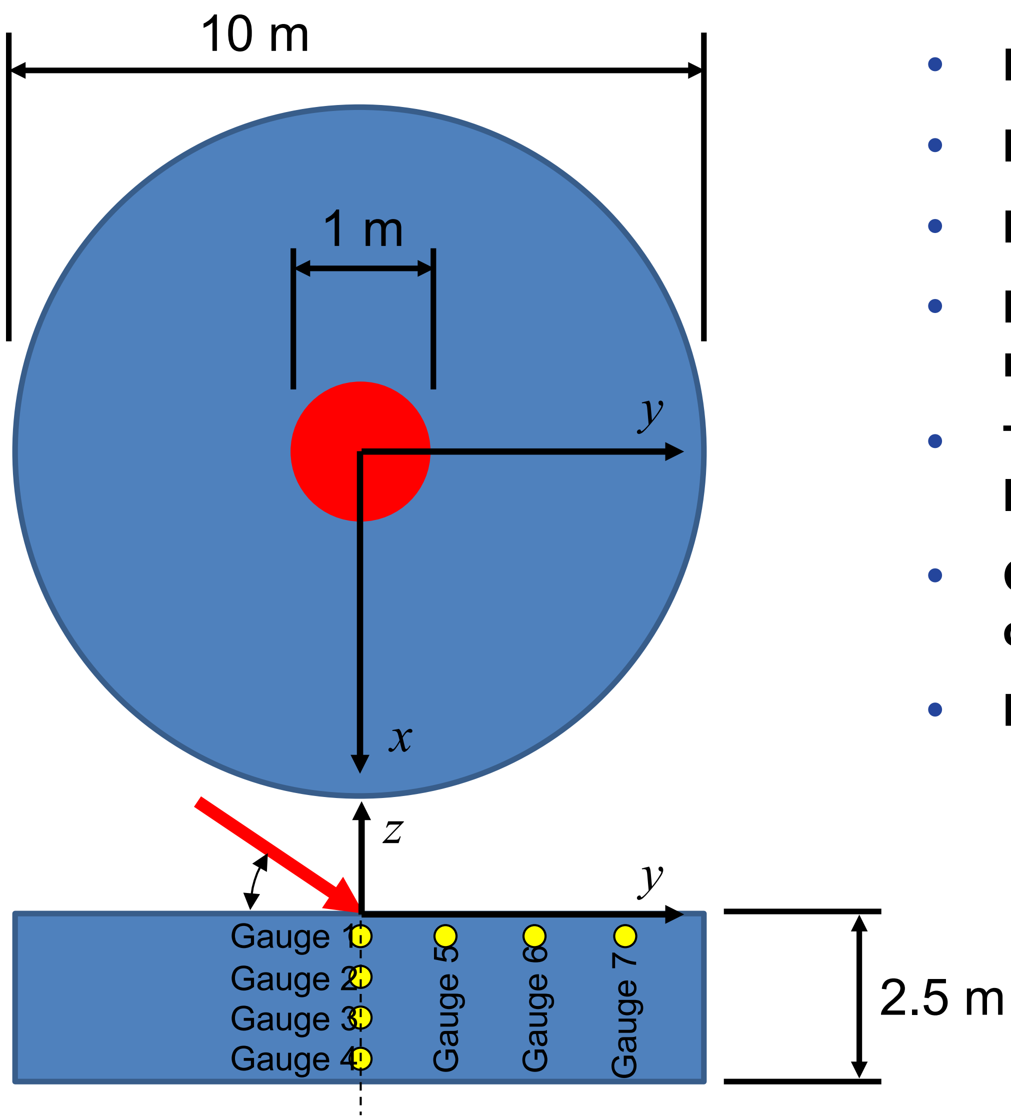
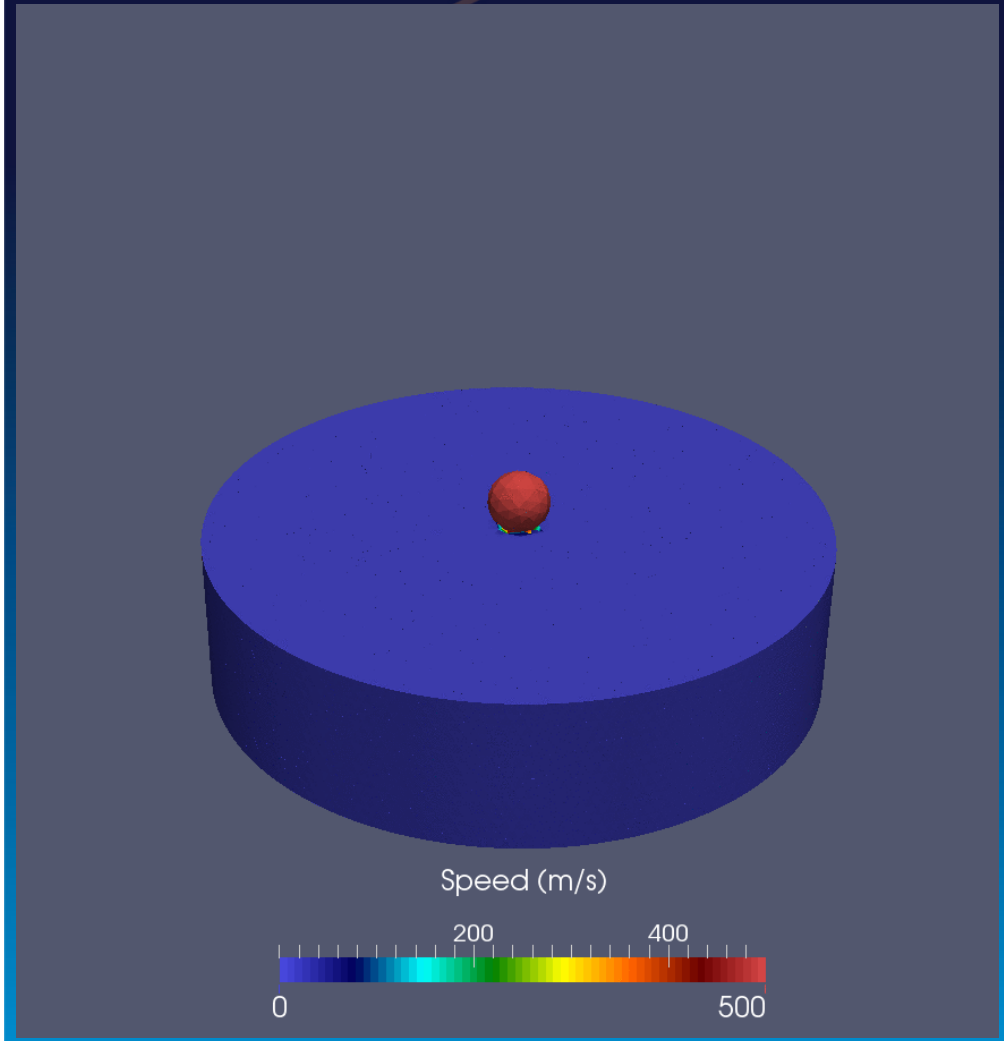
System Setup
Scoping simulations

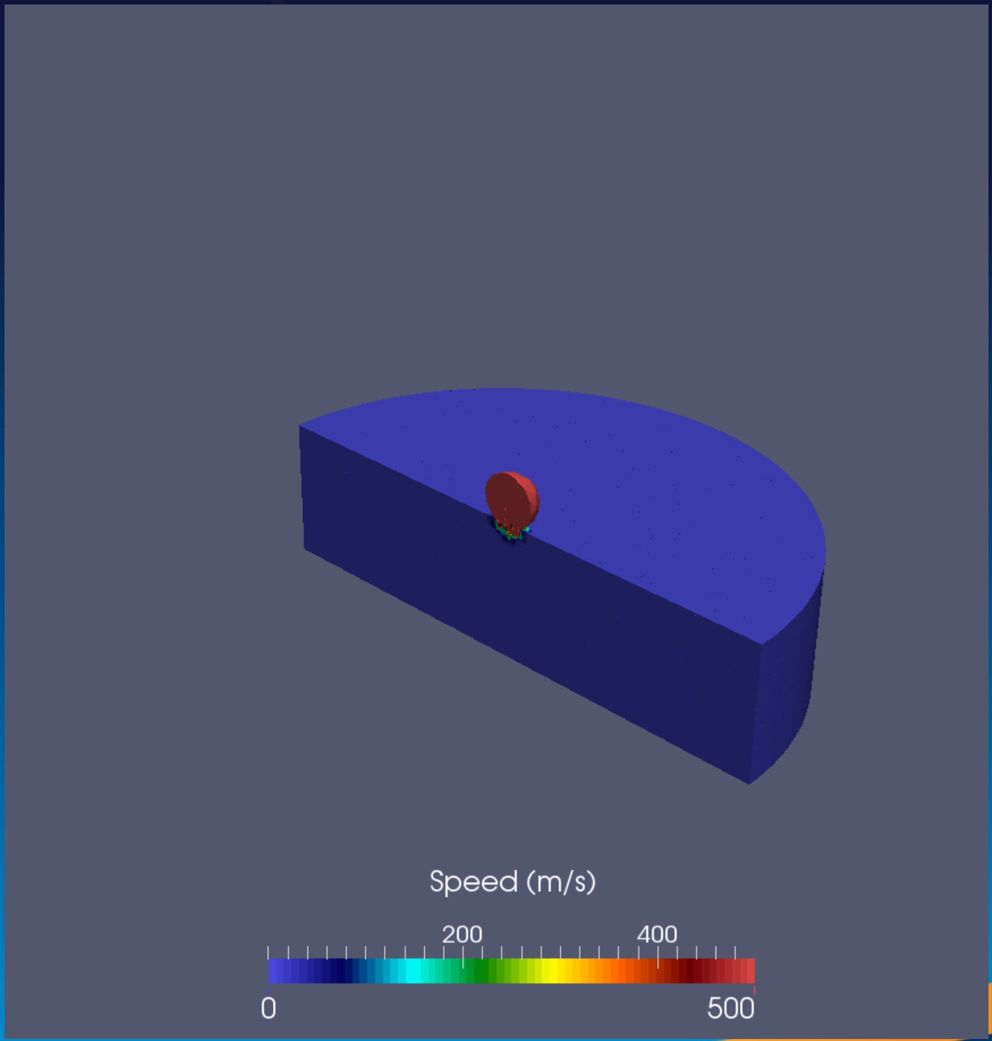


- **No gravity**
- **Impact Speed: 2 km/s**
- **Impact Angles: 45 and 90 deg**
- **Impactor material: cohesion-less rock-like**
- **Target material: cohesion-less rock-like**
- **Geometry was upscaled for the sake of demonstration purposes only.**
- **Future steps:**
  - **Address experiments' scales**
  - **Utilize sand or sandy soil material properties**
  - **Incorporate plastic deformation within finite element formulation**
  - **Verification and validation**
  - **Include effects of gravity**

90 Deg. Impact Angle Results

Scoping simulations





90 Deg. Impact Angle Results
Scoping simulations

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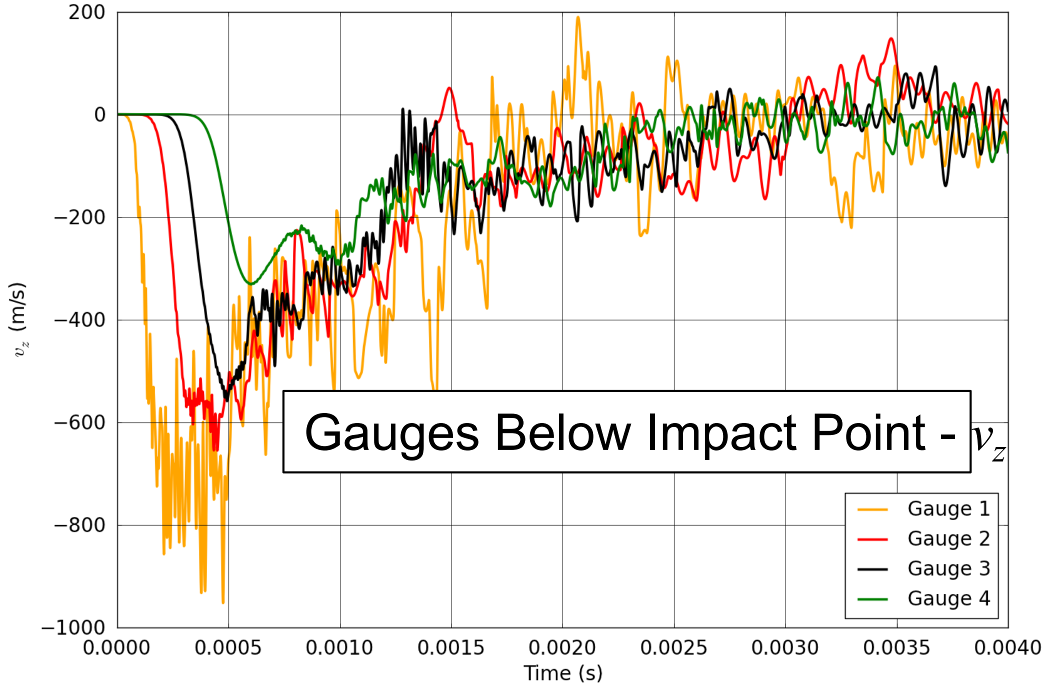
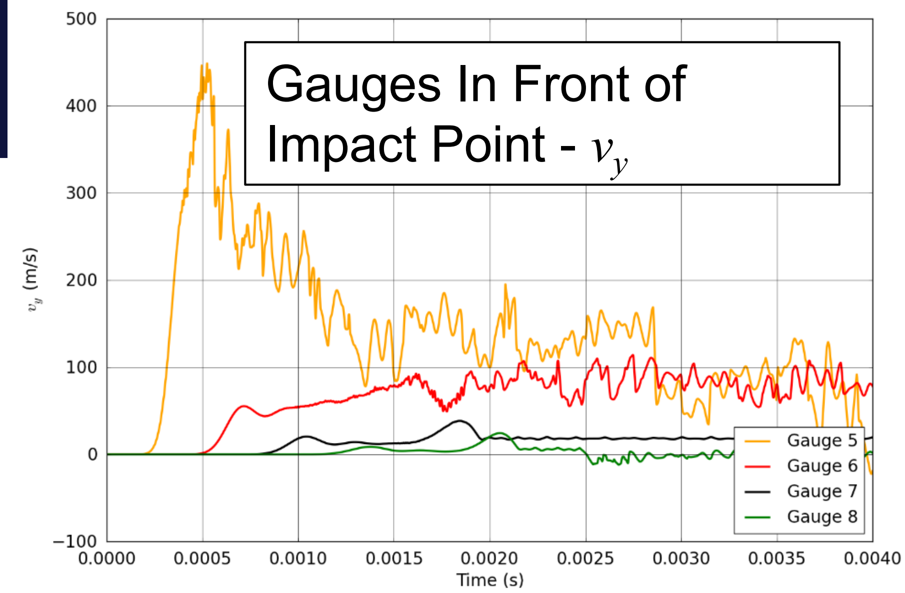
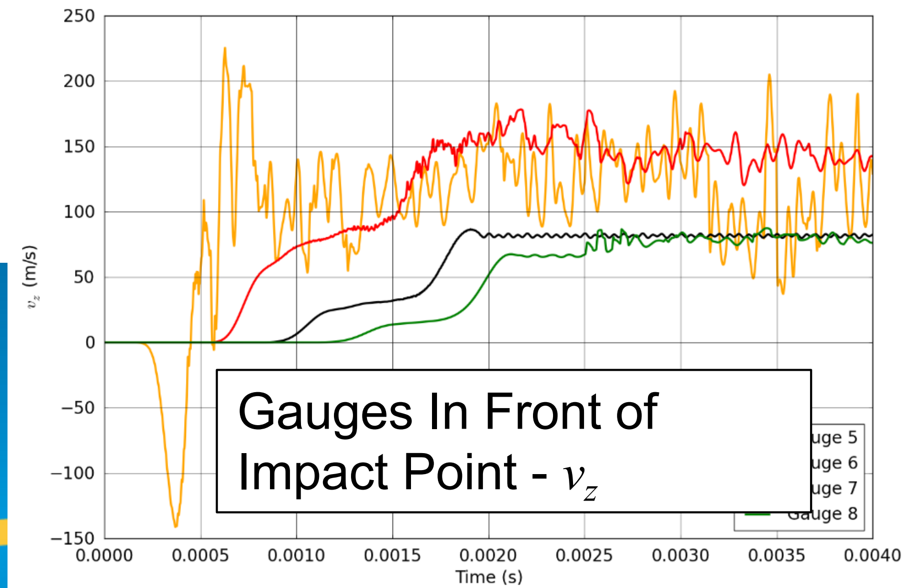
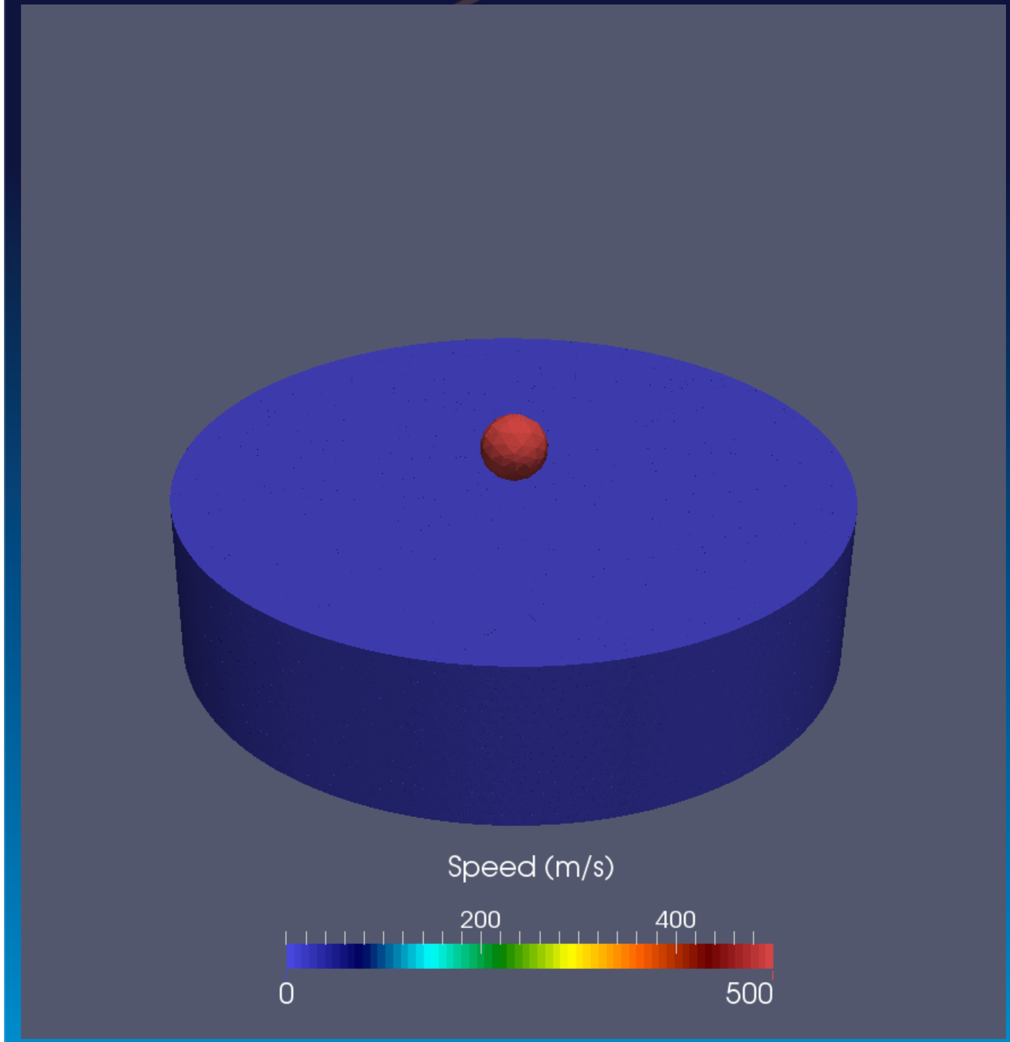


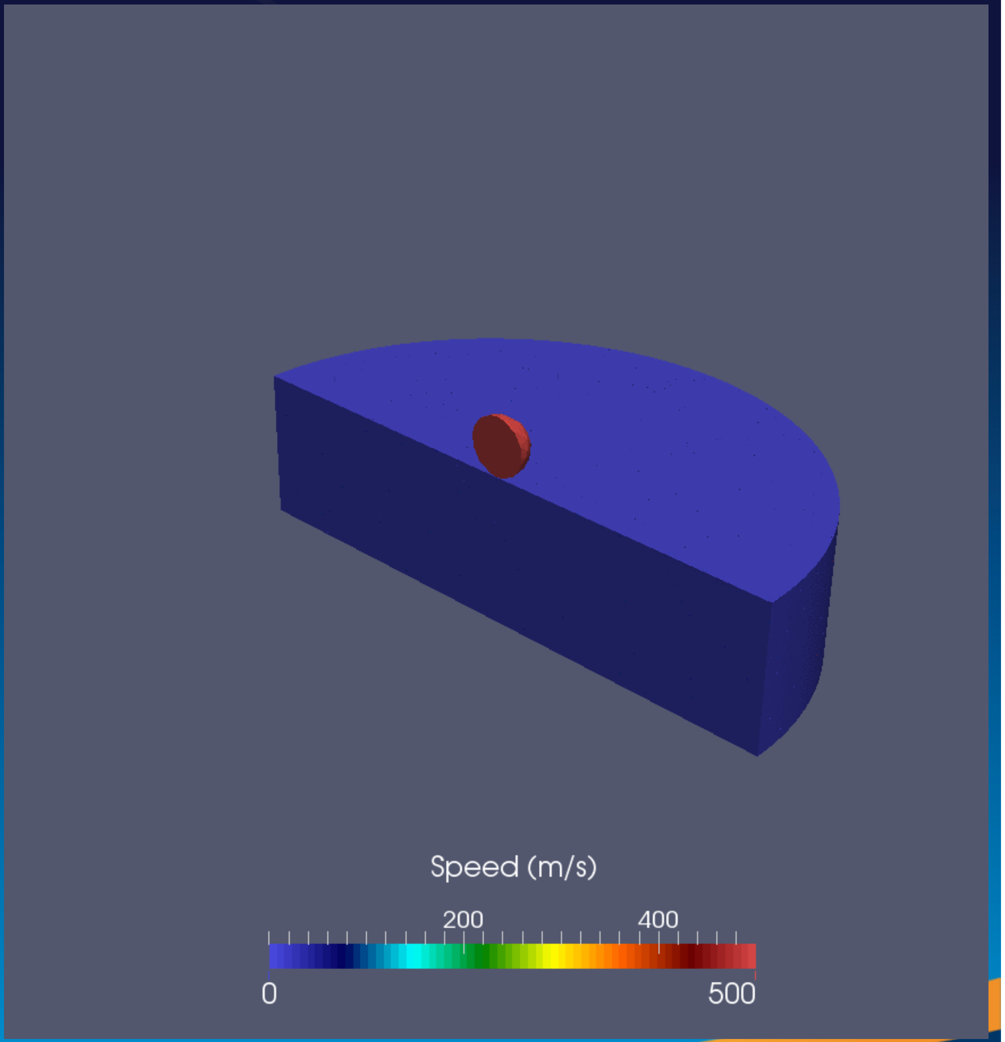




45 Deg. Impact Angle Results

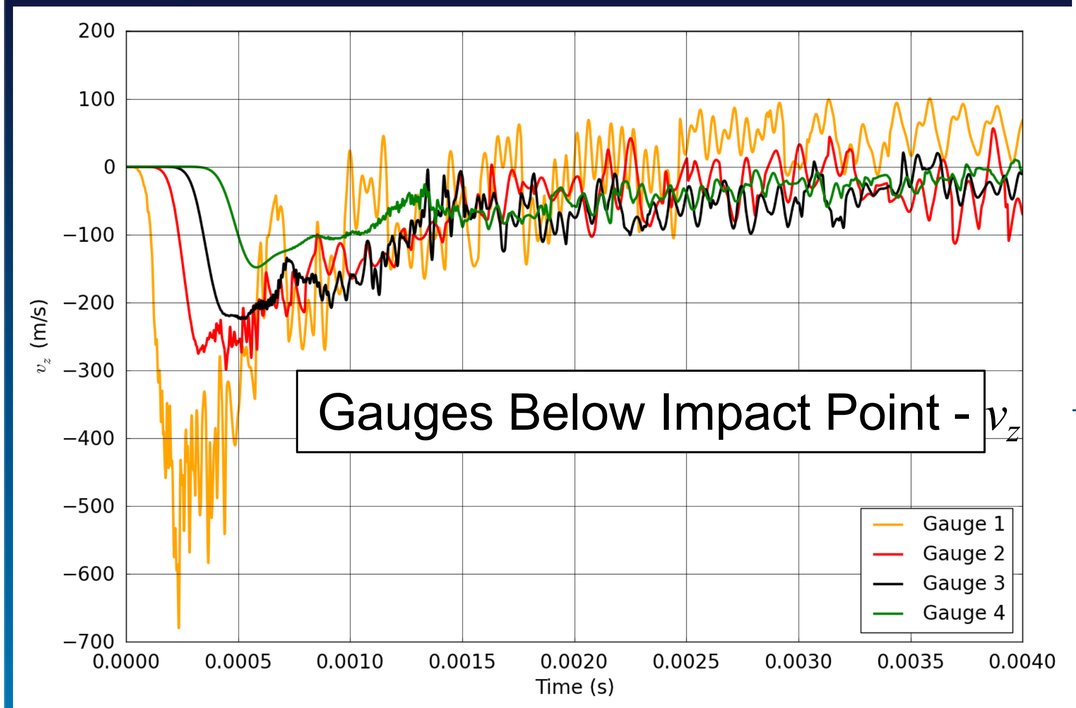
Scoping simulations

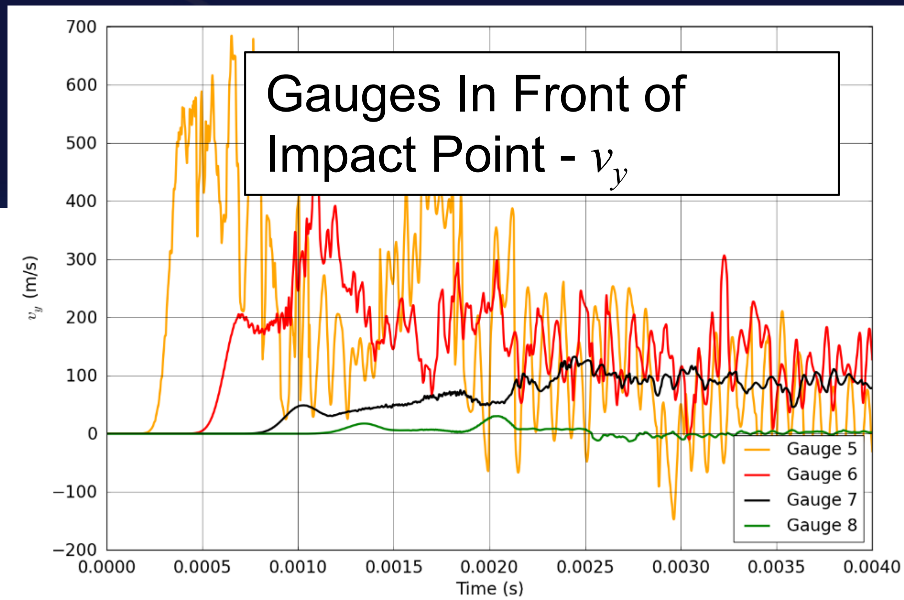


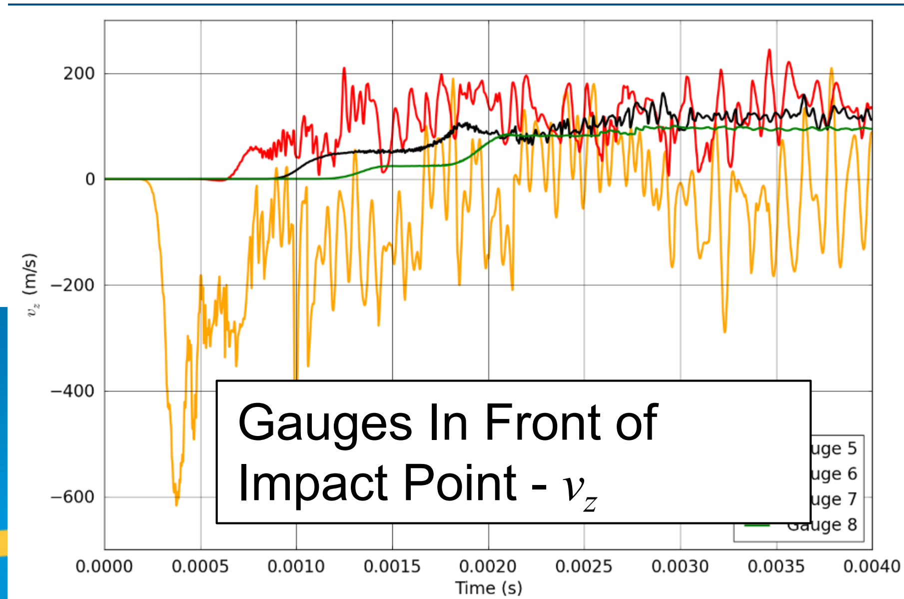


45 Deg. Impact Angle Results

Scoping simulations

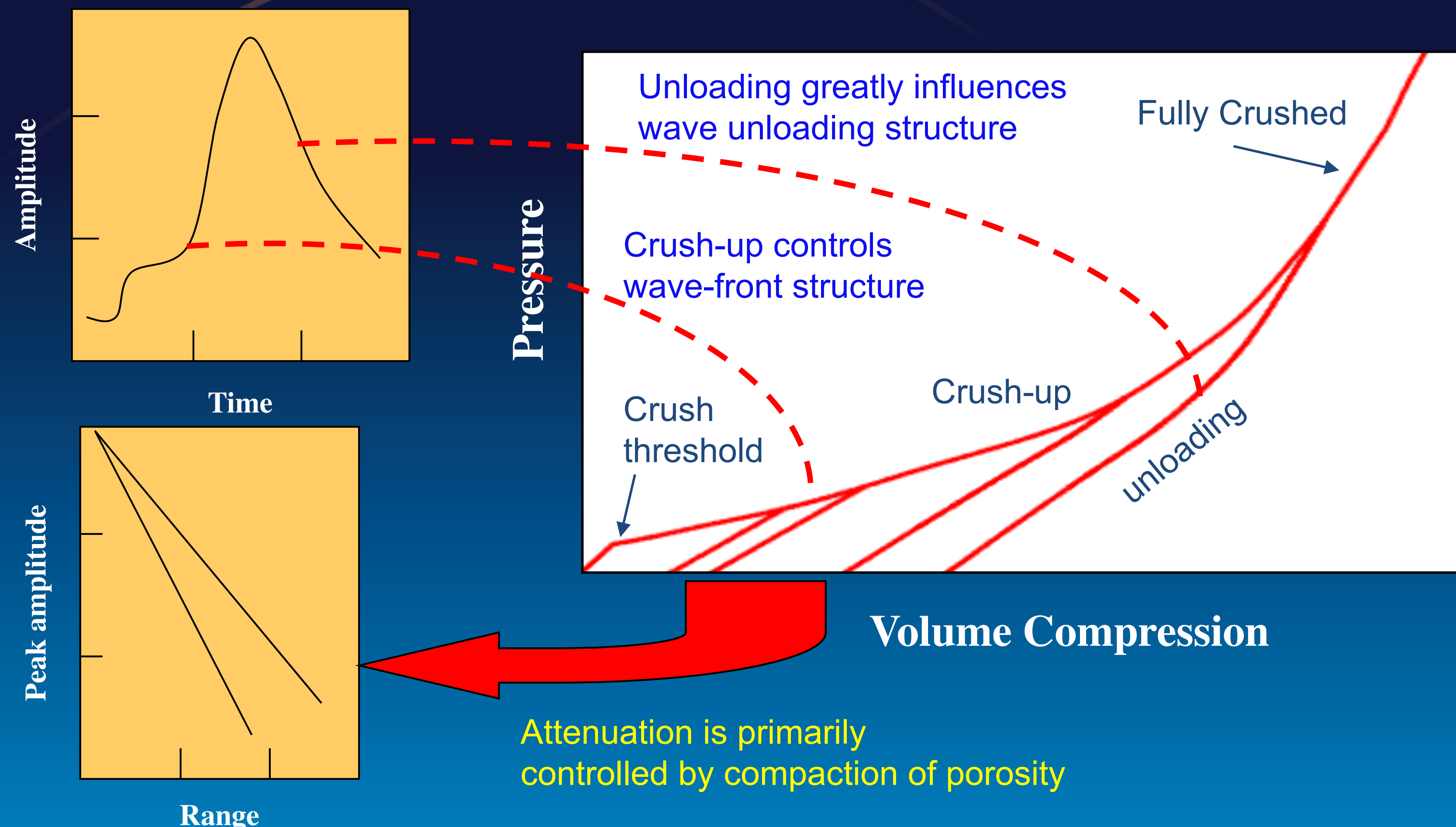






Modeling Impact – Moving Forward

Strongly dependent on Volumetric Behavior



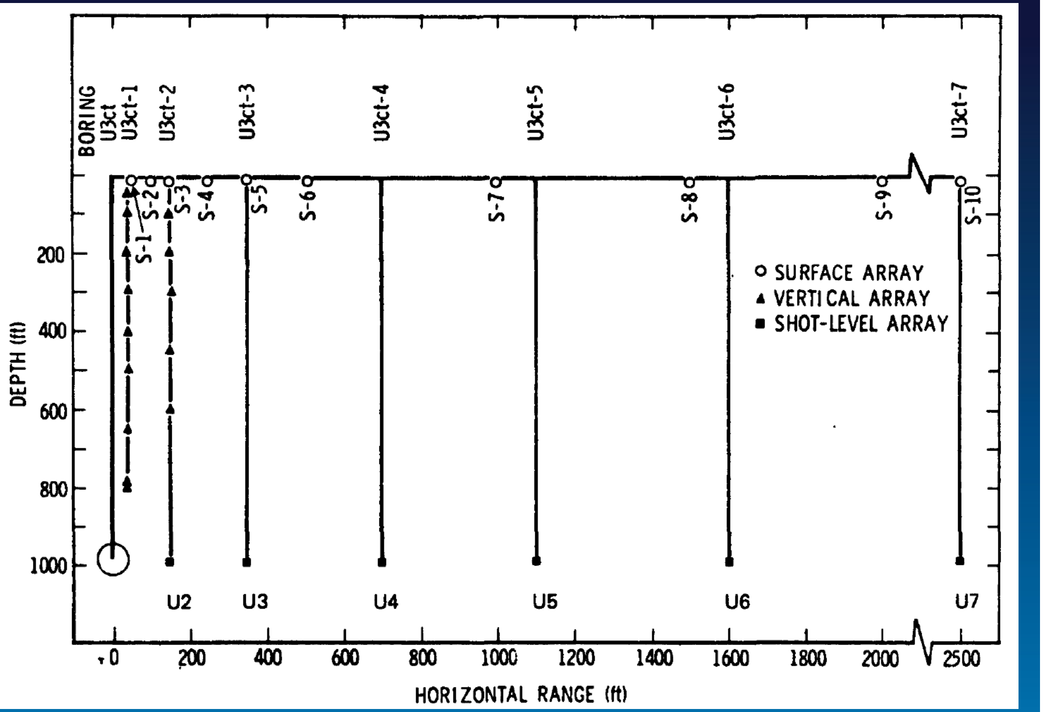
The volumetric response is captured by the equation of state (EOS). The EOS determines the bulk behavior (isotropic) of a geomaterial by calculating pressure as a function of density, or in some cases energy or temperature.

The strength model, on the other hand, calculates the response of the material to the deviatoric components of the stress, i.e., the strength of the geomaterial in shear.

Verification & Validation: MERLIN
App & Brunish, 1991

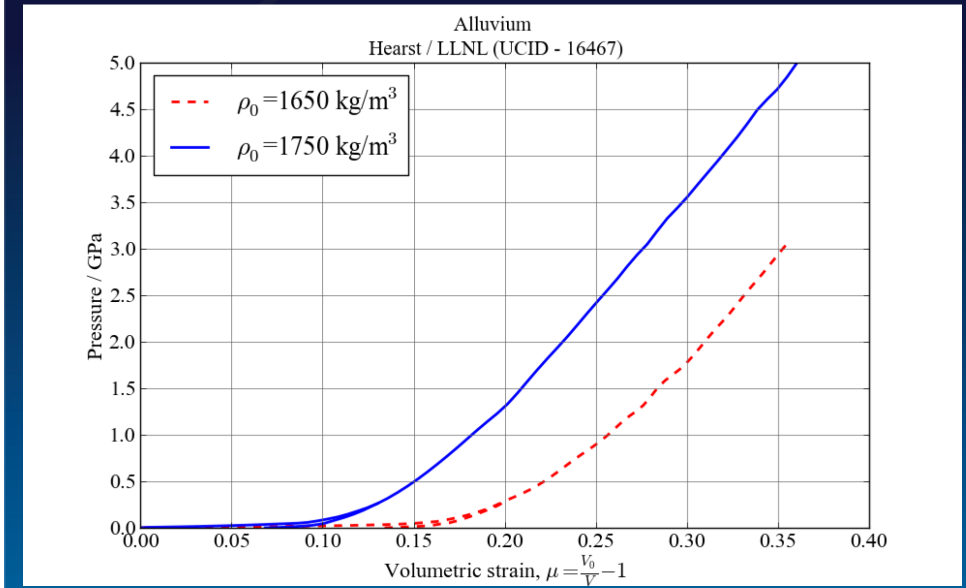
MERLIN NTS Area 3 event in Numbers

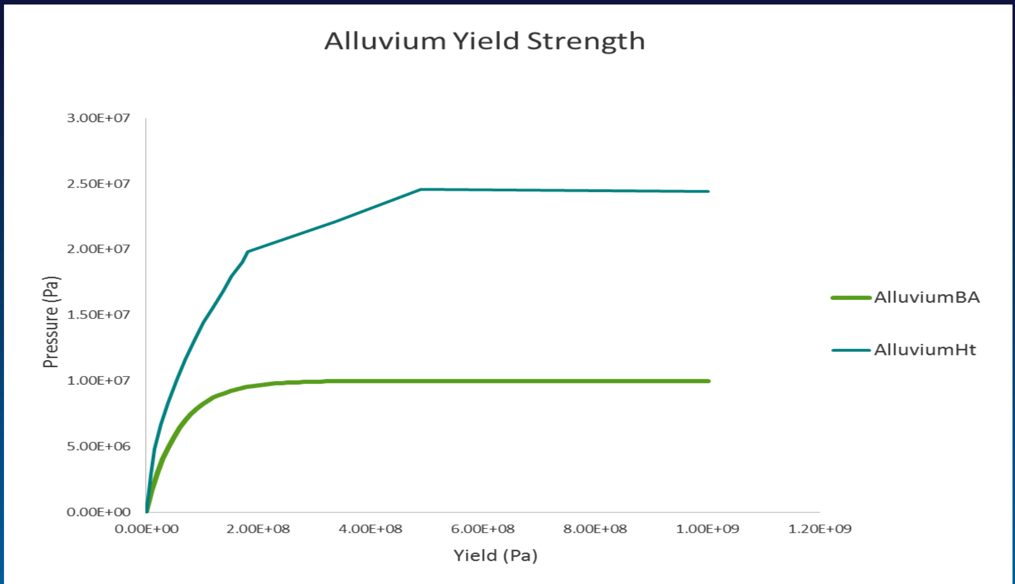
- Depth: 296 m
- Yield Range: 10.0 kt Nuclear – 16 Feb 1965
- Emplacement Medium: Dry Desert Alluvium
- Underlain by Tuff which has a seismic impedance 40% greater than alluvium



From SAND 74-0252 "Free-Field Ground Motion induced by Underground Explosions," Perret & Bass.

Alluvium Soc-Crush EoS
Hydrostatic and Deviatoric Response



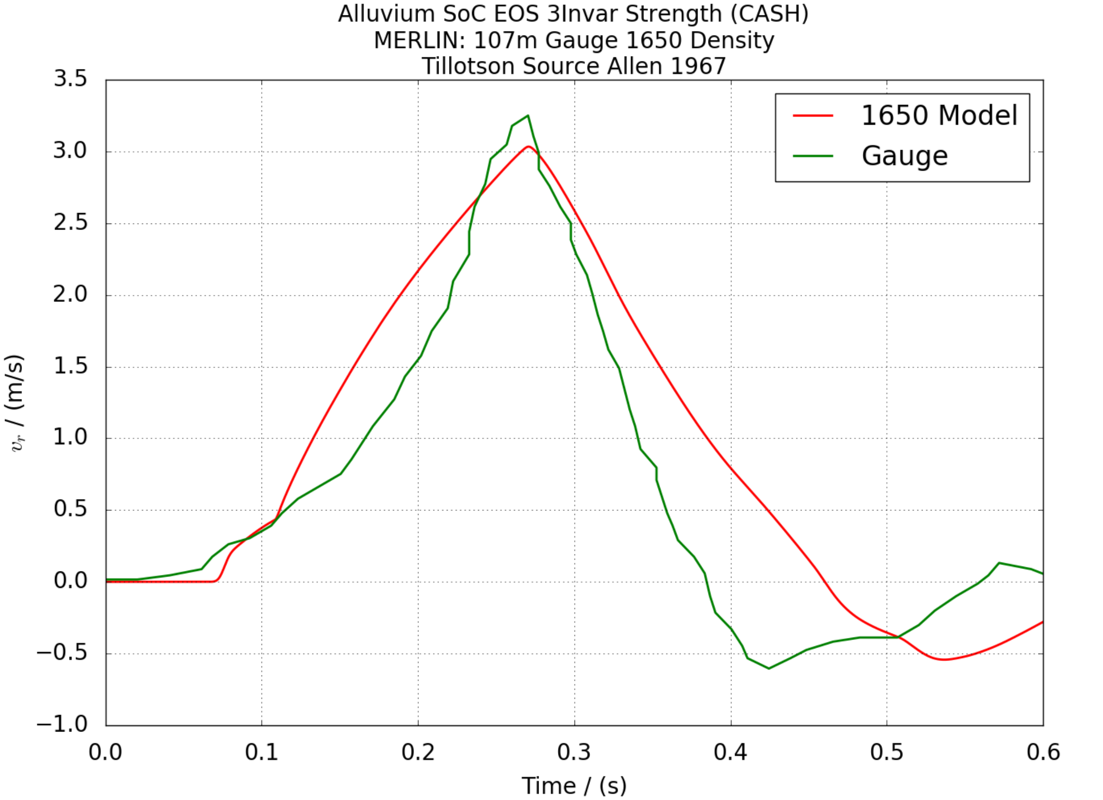


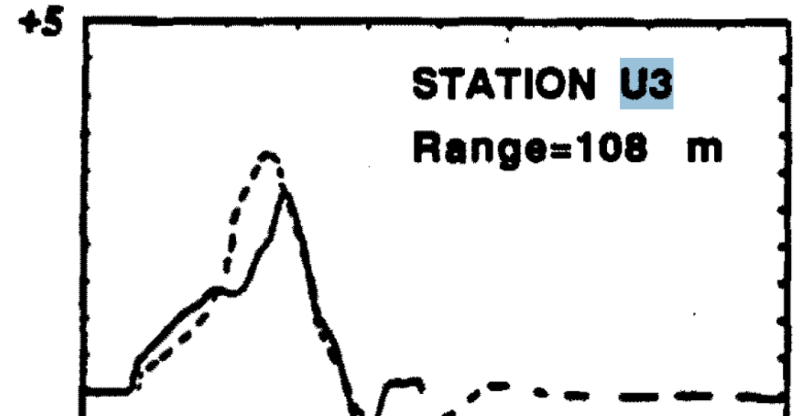
The material properties for the alluvium are:

Bulk Modulus: 5.718e8 Pa
Shear Modulus: 3.876e8 Pa
Density: 1650.0 kg/m3

Poisson Ratio: .21
p-wave speed: 800.0 m/s
s-wave speed: 485.0 m/s

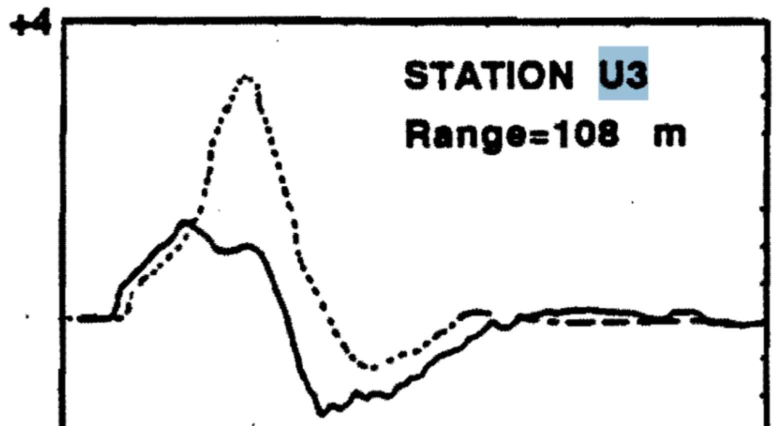
MERLIN
Comparison versus Past Analysis





1D calculation result: solid line.

From "Stress Wave Calculations of Four Selected Undergound Nuclear Tests," App & Brunish. Dashed line is event signal.



2D calculation result: solid line.

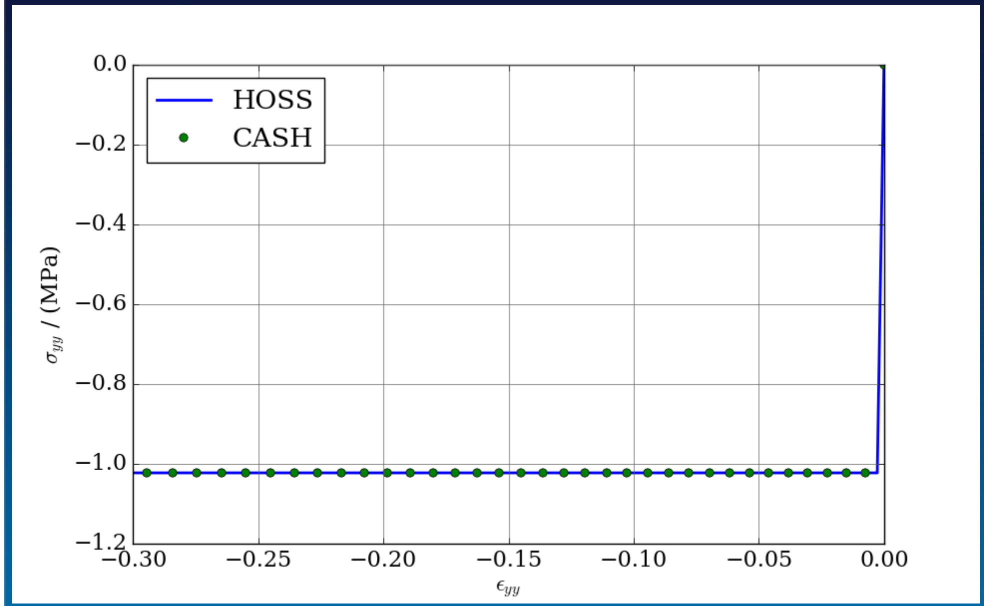
HOSS – Material Model Porting

- Coding effort began January
- Three Material models (3 Invariant strength, DryRock damage models, and Von Mises) together with two EoSs (SocCrush and Linear Us-Up) have been ported to HOSS
- Testing in HOSS (Single Cell) compression and tensile now complete

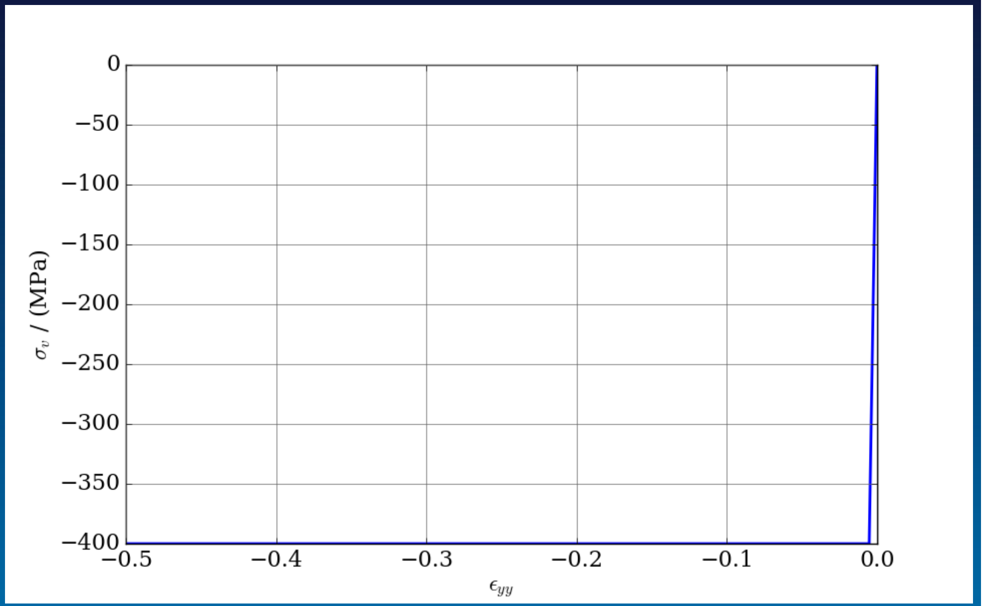
HOSS – Material Model Porting

Benchmarking – Uniaxial Compression

3-Invars + SocCrush

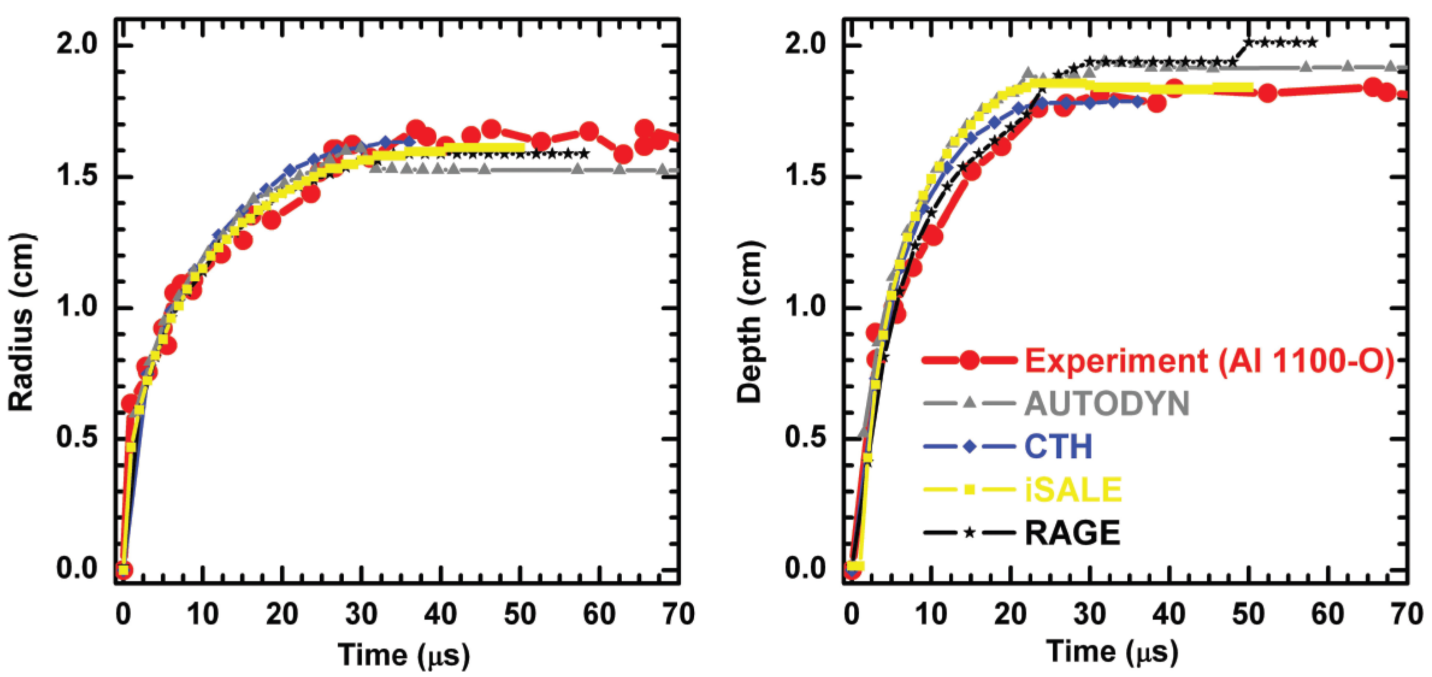


Von Mises



- Single Cell Uniaxial Compression results obtained with HOSS perfectly match those from the other approaches (CASH/Theory)

HOSS Simulations – Next Steps
Validation: Aluminum-into-Aluminum



Temporal evolution of crater radius and depth for the impact of an aluminum projectile on a target made of Al-1100 which has a strain rate dependent strength.

- **Objective: to validate HOSS models against experiments as suggested by the paper "Validation of numerical codes for impact and explosion cratering: Impacts on strengthless and metal targets"**
- Catherine Plesko (XTD-NTA) is serving as a SME advisor for the project

HOSS Simulations – Next Steps

Verification: JPL Lab Experiment

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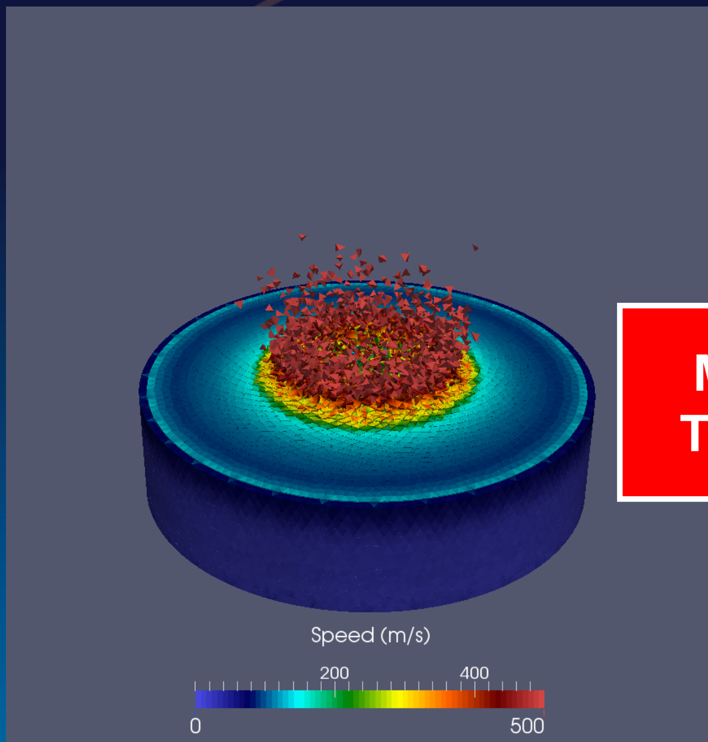

Moving Towards

- **Previous work assumed the material is elastic**
- **Future simulations will incorporate the newly developed material models to better describe the behavior of the unconsolidated material**

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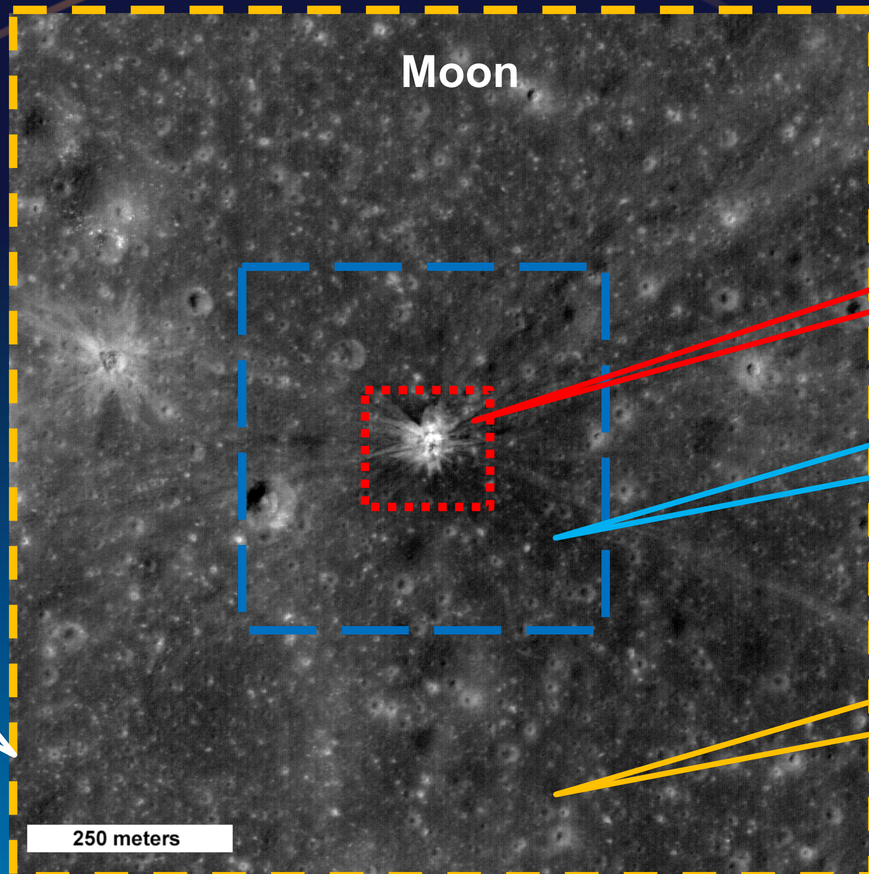
HOSS Simulations – Next Steps

Lunar Impacts: Saturn IVB and Meteorites

Saturn IVB



Data collection for SPECFEM3D

Near Crater Domain
Unconsolidated Material
FDEM

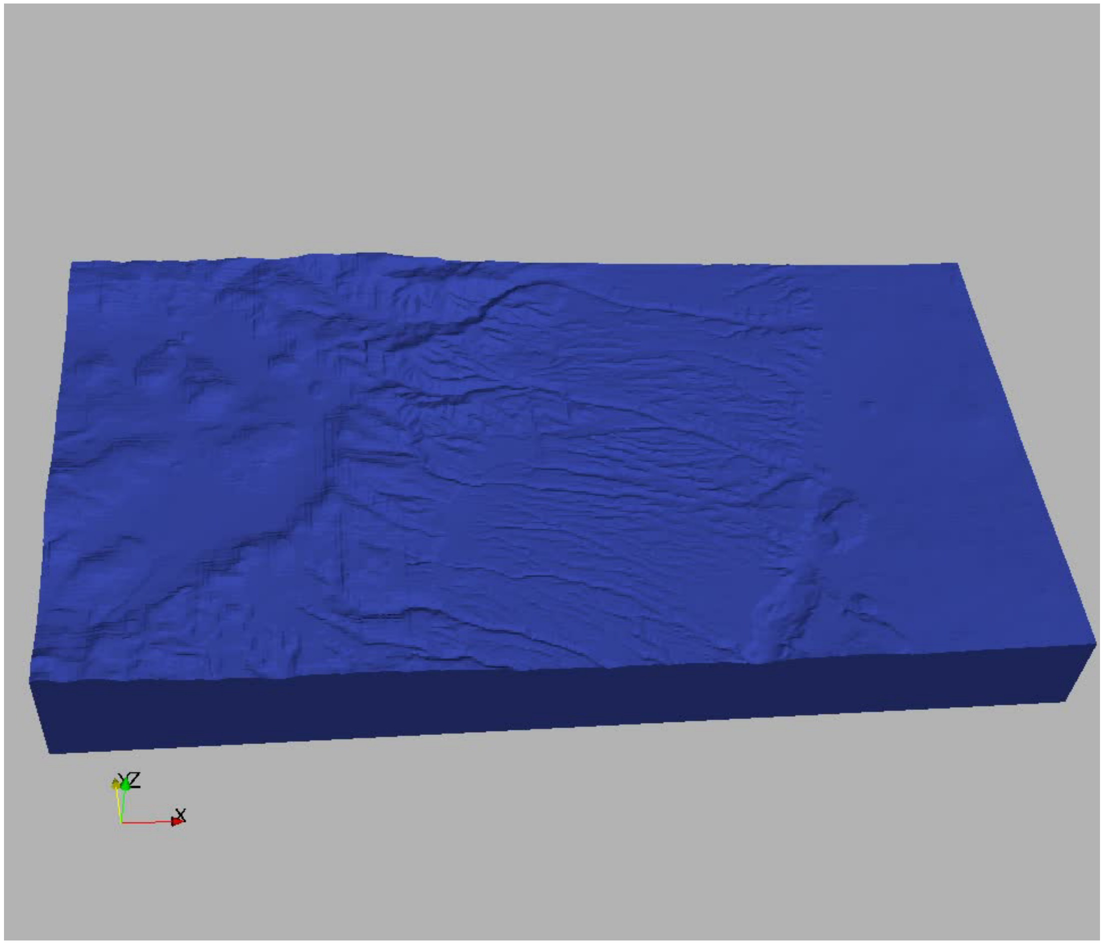
Near Impact Domain
Plastic Material
FEM

Far Impact Domain
Elastic Material
FEM

- **The Apollo 14 S-IVB booster was 17.8 m tall and 6.6 m in diameter and weighed about 14,000 kg. It was launched on January 31, 1971 and was directed to impact the Moon on February 4, 1971.**
- **Multi-domains approaches in 2D/3D will be utilized to obtain enough resolution with relative low computation cost**

far-field full wave 3D modeling, SPECFEM3D

- Spectral Element Method, minimized dispersion for complex boundaries (i.e. free surface with topography) compared to Finite Difference
- SPECFEM3D package: maintained open-source code by CIG, heterogeneity in the crust and mantle, topography, anisotropy, attenuation, fluid-solid interactions, self-gravitation, rotation, and the ocean load.
- Interfaced with other codes done through continuity of displacement
- Used for modeling of seismicity on Mars (Larmat et al., 2006, Icarus), new models are developed for Mars (Insight Mission), Venus.



example of modeling involving interaction with 3D structure and topography

Computational Physics Workshop

- **June 12, 2017 to August 18, 2017. $24k. Managed by the XCP group. POC: James L. Hill, jimhill@lanl.gov**

- Kelsey Neal, Colorado School of Mines
- Vijay Shah, North Dakota State University

- **Student 1: benchmark Aluminum impact on Aluminum (Pierazzo et al. 2008)**
- **Student 2: 2D full modeling of MERLIN event with handover to SPECFEM3D. Modeling of global Moon wave propagation.**

Anticipated Impact

We aim to reduce the uncertainty of impact models by, at least, an order of magnitude, making seismic exploration more reliable and therefore more likely to be included in future NASA missions.

- *This result will come from the use of our numerical models based on first principle physics and on a minimum set of assumptions. The remaining source of uncertainty will be modeling parameters, not the physics.*
- *Seismology is one component of geophysics exploration that allows us to link our knowledge of the surface to deeper parts of planetary and rocky bodies.*
- *End-users are NASA, CTBTO, NNSA, AFTAC*